DESIGN OF PERIODICALLY CORRUGATED DIELECTRIC ANTENNAS FOR MILLIMETER-WAVE APPLICATIONS

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ABSTRACT

Periodic dielectric waveguide structures were extensively analyzed and were understood in the context of integrated-optics theory. Recently, it has been also demonstrated experimentally that this class of structures offer many advantages for use as millimeter-wave antennas. A considerable effort is currently under way to fully develop its potential. Making use of the available analytic method previously devised, we have carried out an extensive and systematic analysis of periodically corrugated dielectric antennas. The results are exhibited in a way that is most pertinent to millimeter-wave applications. On the basis of the obtained numerical data, a set of design guidelines for the corrugated dielectric antennas is established herein.

1. Introduction

A dielectric waveguide with a periodic perturbation, or simply a periodic dielectric waveguide, has been shown to hold substantial promise as a leaky-wave antenna for millimeter applications[1-5]. Such an antenna structure may be conveniently fabricated on a uniform dielectric waveguide to form a completely integrated mm-wave system. In addition, the dielectric leaky-wave antennas offer the advantage of electronic beam steering[1,2]. Therefore, in recent years, a considerable effort has been made for a better understanding of this particular class of antennas in order to explore its applications to mm-wave systems.

In this paper, we present a systematic analysis of the periodically corrugated dielectric waveguide for use as a leaky-wave antenna for mm-wave applications. We recognize that this class of structures has been extensively analyzed for integrated-optics applications[7] such as beam-to-surface-wave couplers, distributed feedback reflectors, and filters. In fact, leaky-wave antennas and optical periodic couplers are based on the same physical principle[4,7] and a great deal of information on the basic wave characteristics of the optical devices can simply be carried over for the understanding of the mm-wave antennas. However, because of the substantial difference in the permittivity of the materials commonly used in the two frequency ranges and because of different processes by which these devices are

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constructed, the design procedures for mm-wave antennas differ from that for optical couplers in many respects. The main purpose of this paper is to make use of the existing theoretical tools[4,7] for developing design guidelines for the particular class of corrugated dielectric leaky-wave antennas, appropriately taking into account special requirements for mm-wave applications.

For mm-wave applications, a corrugated dielectric antenna has ,at most, a few wavelengths in width, in contrast to thousands of wavelengths for most optical couplers. Therefore, an optical periodic coupler can be formulated as a two dimensional boundary value problem that may support independent TE or TM modes propagating normally to the grooves of the corrugation. It has been shown[8,9] that to investigate the effect of finite antenna width, the most basic problem to be solved is the guiding of waves propagating at an oblique angle in an infinitely wide periodic structure. This is a three dimensional electromagnetic boundary value problem that supports only hybrid modes, e.g., it requires the coupling between TE and TM modes. Such a vector boundary value problem has been formulated[8] and the propagation characteristics for the general case of oblique guidance have been subsequently analyzed. The effect of the finite antenna width on the performance of the corrugated dielectric antenna has been reported[9]. It has been shown[8,9] that for an antenna structure of finite width, the longitudinal phase constant is determined by the

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unperturbed uniform waveguide and the decay constant does not differ from that of the two-dimensional case, as long as the width of the antenna is not very small. In this work, we shall assume that the antenna width is large enough so that the leakage constant can be obtained from the simpler normal guidance case.

2. Design of the periodically corrugated dielectric antenna

The configuration of a dielectric antenna structure is shown in Fig.1. Such an electromagnetic structure has been previously analyzed in the context of optical periodic couplers[7] and many radiation characteristics of the structure have been known. The antenna structure is characterized by four parameters : the thickness of the uniform region, t_f, the thickness of the corrugation region, t_g, the period of the corrugation, d, and the aspect ratio $a = d_1/d$. Since the lengths can always be normalized to the free-space wavelength, it is not necessary to consider the frequency of the source as an independent parameter. On the other hand, since a corrugated dielectric antenna is expected to be fabricated from an originally uniform waveguide by machining, it is more appropriate to use the original waveguide height $h = t_g + t_f$ as a parameter. This means that when the waveguide is machined, both t_g and t_f will change. Therefore, it is necessary to investigate the combined effect of change in t_f and t_g on the propagation characteristics of the antenna structure.

Because of the periodicity of the leaky-wave antenna, the electromagnetic fields everywhere must consist of all the space harmonics. For TM modes, we have :

$$H_y(x,z) = \sum_{n=-\infty}^{\infty} I_n(z) \exp(i k_{xn} x) \qquad (1)$$

where I_n is the n-th harmonic amplitude of the magnetic field and k_{xn} is the x-component of the propagation constant of the n-th harmonic and is related to that of the fundamental harmonic by :

$$k_{xn} = k_{xo} + 2n\pi/d = \beta - j\alpha + 2n\pi/d = \beta_n - j\alpha \qquad (2)$$

where β and α are the propagation and attenuation constants of the fundamental harmonic, respectively. It is noted that the propagation constant of the n-th harmonic differs from that of any other harmonic but the attenuation constant, α, is the same for all harmonics. By solving the boundary value problem, it has been shown that k_{xo} and the harmonic amplitudes, $\{I_n \mid n = 0, +1, +2, ..\}$, can be determined in terms of the eigenvalues and eigenvectors of a coupling matrix characterizing the corrugation region. For the given antenna structure on a ground plane of infinite extend, because the energy can only radiate into the air region, it is unnecessary to determine explicitly the harmonic amplitudes, if we are interested only in the case of single beam radiation. In the present study, therefore, we are left with only the determination of the dispersion root k_{xo} of the antenna. For simplicity, k_{xo} will be referred to as the leaky wave constant. Since α may be used as a measure of

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the rate of energy leakage, it will also be called the leakage or radiation constant, in constrast to the phase constant β.

In the air region where the medium is uniform, each harmonic propagates independently as a plane wave. The transverse propagation constant of the n-th harmonic is given by :

$$K_{zn} = (k_o^2 - k_{xn}^2)^{1/2} \qquad (3)$$

For a very shallow corrugation or t_g very small, it is intuitively expected that $k_{xo} = \beta_{sw} = K_o n_{eff}$, where β_{sw} is the longitudinal propagation constant of the unperturbed structure, as shown in Fig.2. Under such an approximation and invoking (2), we obtain, from (3) :

$$K_{zn} = K_o[1 - (n_{eff} + n\lambda/d)^2]^{1/2} \qquad (4)$$

For only the n = -1 harmonic to radiate, we must have $K_{z,-1}$ real and all K_{zn} imaginary for n $\neq$ -1. These conditions can alternatively be expressed as :

$$\frac{\lambda}{n_{eff} + 1} < d < \frac{\lambda}{n_{eff} - 1} , \qquad \text{for } n_{eff} > 3 \qquad (5)$$

$$\frac{\lambda}{n_{eff} + 1} < d < \frac{2\lambda}{n_{eff} + 1} , \qquad \text{for } n_{eff} < 3 \qquad (6)$$

Under these conditions, the n = -1 harmonic radiates into the air region at an angle (with respect to the z-axis) :

$$\theta_{rad} = \sin^{-1}(\beta_{-1}/k_0) = \sin^{-1}(n_{eff} - \lambda/d) \qquad (7)$$

The sign of θ_{rad} determines the forward or backward radiation. Although the above design formulas are derived under the assumption that t_g is very small, they also hold for t_g large, if the normalized phase constant or the effective index of refraction, n_{eff}, is accurately obtained for a given t_g.

It is noted that n_{eff} of a periodic dielectric waveguide does not depend appreciably on the period d of the structure. Eq.(7) shows that the choice of the period d is simply determined by the radiation angle. Therefore, the effect of the period d on the antenna performance will not be further elaborated.

2.1. Effect of the corrugation thickness t_g on the radiation angle

As a uniform slab of the thickness h is machined, the dielectric material is scooped out. As a result, the effective thickness of the corrugated slab is reduced, and so is the effective dielectric constant. It has been well known[4,7] that the effective dielectric constant of the corrugated slab may be simply determined by a uniform double layer structure with the volume average of the dielectric constant for the periodic corrugation region. As an example, Fig.2 shows the effective dielectric constant as a function of the corrugation thickness for a periodic silicon slab with the aspect ratio $d_1/d = 0.5$. In Fig.2, the solid

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curves are for fixed thickness of the origional slab, $h = t_f + t_g$, as a parameter, whereas the dashed curves are for fixed thickness of the uniform portion of the corrugated structure. For example, in the case of an originally uniform slab of thickness $h = 0.2\lambda$, a corrugation of the thickness $t_g / \lambda = 0.05$ and an aspect ratio $a = d_1 / d = 0.5$ will result in an antenna structure with an effective dielectric constant $\epsilon_{eff} = 10$, as marked by the cross labelled by A on the curve for $h / \lambda = 0.2$ in Fig.2. The same effective dielectric constant can be achieved by other combinations of h and t_g values, such as $h/\lambda = 0.24$ and $t_g / \lambda = 0.1$, as marked by the cross labelled by B in Fig.2. It is noted that the dashed curves are useful for the design of other types of structures, and will not be further elaborated here. After $\epsilon_{eff} = n_{eff}^2$ is determined for a given antenna structure, the radiation angle is determined according to (7). Thus, the set of solid curves provides the necessary information for determining the dependence of the radiation angle on the corrugation thickness.

2.2. Effect of the corrugation thickness on the radiation constant

It has been known[1-5] that the radiation constant α is proportional to t_g^2, for t_g small, and reaches a saturation value for t_g large, if the guided-wave field is evanescent in the corrugation region. For the aspect ratio $d_1/d = 0.5$, the average dielectric constant of the corrugation region is

ϵ_{ave} = 6.5, and the guided-wave field is indeed evanescent in the corrugation region. The radiation constant as a function of the corrugation thickness is shown in Fig.3. Evidently, the radiation constant α varies with the corrugation thickness t_g in the fashion expected.

On the other hand, the fabrication of a periodically corrugated dielectric antenna by machining changes not only the thickness of the corrugation region, but also that of the uniform region. Therefore, it is necessary to consider the combined effect of the changes in both the thicknesses of the corrugated and uniform regions. When a uniform dielectric slab is cut to produce the corrugation, the thickness of the remaining uniform region decreases at the same rate as the depth of the grooves increases. Based on Fig.3, it is clear that the leakage or radiation constant will increase initially as the grooves are cut deeper and deeper. However, because of the changing thickness of the remaining uniform portion that affects the basic surface wave, it is not clear at this point that if the radiation constant is still too small, any further cut can be helpful for achieving a larger radiation constant.

Fig.4 shows the variations of the radiation constant and the radiation angle θ_{rad} as the thickness of the corrugation region t_g is increased, for the case of the original thickness h = 0.3λ, the period d = 0.25λ, and the aspect ratio d_1/d = 0.5. When the grooves are shallow (t_g small)

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the solid curve shows that the radiation constant α increases with the groove depth, as expected. However, α reaches a maximum value at $t_g \approx 0.1\lambda$ and then decreases a t_g is further increased. Such a decrease in α can be explained as follows : As t_g is increased, the remaining uniform portion of the structure becomes thinner and thinner and, as a result, the phase constant of the guided wave becomes smaller and smaller. This phenomenon is exhibited by the dashed curve for the radiation angle in Fig.4. More specifically, the radiation angle increases in the backward direction with increasing t_g. Eventually, the antenna struc- ture will cease to radiate in the backward end-fire direc- tion and the guided wave becomes totally bounded.

Fig.5 shows the results for a case of a thinner origi- nal uniform slab, $h = 0.25\lambda$, while all other structure parameters are kept unchanged from the proceeding case. However, it is interesting to observe that the maximum value of α occurs at the same thickness of the remaining uniform slab $t_f = 0.2\lambda$ in both cases. In fact, this result holds for any structure with $d = 0.25\lambda$ and $d_1/d = 0.5$, as long as the thickness of the original uniform slab is sufficiently large.

2.3. Effect of the aspect ratio

The numerical results presented in the preceeding sec- tion are all for the case of equal width for the teeth and grooves or the aspect ratio $d_1/d = 0.5$. In the fabrication

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process, the aspect ratio can be easily controlled, if
. .... For comparison purpose, the radiation constant α as
a function of the groove depth t_g is shown in Fig.6 for an
original uniform slab of the thickness h = 0.25λ and the
period d = 0.25λ as in Fig.5, but with wider teeth (d_1/d
0.8) or narrower grooves. With such a new aspect ratio, the
attainable maximum value of α is increased by a factor of
about 4 from the case of $d_1/d = 0.5$, but the grooves have to
be cut deeper ($t_g \approx 0.1\lambda$).

In order to fully understand the effect of the aspect
ratio, the radiation constant as a function of the aspect
ratio is investigated and the results are plotted in Fig.7,
for the structure and parameters indicated. In the two lim-
iting cases of the aspect ratio : $d_1/d = 0$ and 1, the
periodic structure becomes uniform and it is expected that
no radiation can occur. For optical structures with a rela-
tively low dielectric constant, it is well known[7] that the
maximum radiation occurs at the aspect ratio $d_1/d = 0.5$.
For mm-wave antennas, however, the dielectric constant is
relatively high and the field variation in the corrugation
region depends strongly on the aspect ratio, and so does the
radiation constant. Fig.6 shows that the value of α peaks
around the aspect ratio $d_1/d = 0.7$, instead of $d_1/d = 0.5$ as
usually expected. Such a shift in the aspect ratio can be
explained qualitatively as follows : For the given struc-
ture, the fields in the corrugation region are evanescent
for the aspect ratio $d_1/d = 0.5$; therefore, the surface wave

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is only weakly perturbed by the corrugations and the radiation constant is small. When the aspect ratio is increased, more surface-wave energy is shifted to the corrugation region, resulting in a larger perturbation of the surface wave and a larger radiation constant. Thus, we may conclude that for a larger radiation constant, the aspect ratio should be relatively large ($d_1/d > 0.5$) or the grooves should be relatively narrow.

3. Discussions and conclusions

The radiation characteristics of thick corrugated dielectric antennas are relatively insensitive to the change of structure parameters. From the practical viewpoint, this property will afford a larger tolerance in a mass production of the antennas. On the basis of the numerical results presented above, we may now establish the following general guidelines for the design of the corrugated dielectric antenna structures:

(1) The thickness of the original uniform slab and the period of the corrugation are determined by the desired radiation angle according to (7).

(2) For a uniform dielectric slab, there exists a groove depth t_g that yields a maximum value of radiation constant; a desired radiation constant

smaller than the maximum value may be realized

by a larger or smaller value of t_g, depending on

the radiation angle desired.

(3) Within the constraint of the radiation angle, the

larger the thickness of the original uniform slab,

the larger the maximum value of the radiation

constant α achievable.

(4) There exists a groove width or an aspect ratio

that yields a maximum value of the radiation

constant α and a smaller value of α may be

realized by adjusting the aspect ratio.

(5) For a uniform dielectric slab of larger thickness

and high dielectric constant, the maximum value

of α occurs with the groove width smaller than

the tooth width. In other words, cutting the groove

with a larger width may not help increase the

radiation constant.

In addition to those presented above, we have carried

out extensive numerical results for many different

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situations. In particual , for the case of relatively thin antenna structures, the radiation characteristics are generally much more sensitive to the change of structure parameters, and each structure has to be quantitatively evaluated individually. Therefore, general design guidelines for thin corrugated dielectric antennas are difficult to develop.

Acknowledgement

Reference

1.   Klohn, K.L., Horn, R.E., Jacobs, H. and Freibergs, E., (1978) Silicon waveguide frequency scanning linear array antenna, IEEE Trans. MTT, MTT-26, 764-773.

2.   Horn, R.E., Jacobs, H., Freibergs E. and Klohn, K.L., (1980) Electronic modulated beam-steerable silicon waveguide array antenna, IEEE Trans. MTT, MTT-28, 647-653.

3.   Solbach, K., (1979) E-Band leaky wave antenna using dielectric image line with etched radiating elements, 1979 MTT-S Int. Microwave Symp. Dig., 214-216.

4. Peng, S.T. and Schwering, F., Dielectric (1978) grating antennas, R&d Tech. Report CORADCOM 78-3, U.S. Army CORADCOM, Ft. Monmouth, New Jersey.

5. Mittra, R. and Kastner, R., (1981) A spectral domain approach for computing the radiation characteristics of a leaky-wave antenna for millimeter waves, IEEE Trans. Antennas & Propagation, AP-29, 652-4.

6. Tamir, T., (1975) Integrated optics, Springer Verlag, New York.

7. Peng, S.T., Tamir, T. and Bertoni, H.L., (1975) Theory of periodic dielectric waveguides, IEEE Trans. MTT, MTT-23, 123.

8. Peng, S.T., (1980) Oblique guidance of surface waves on corrugated dielectric layers.

9. Peng, S.T., Oliner, A.A. and Schwering, F., (1981) Theory of dielectric grating antennas of finite width, IEEE AP-S International Symp., L.A., C.A.
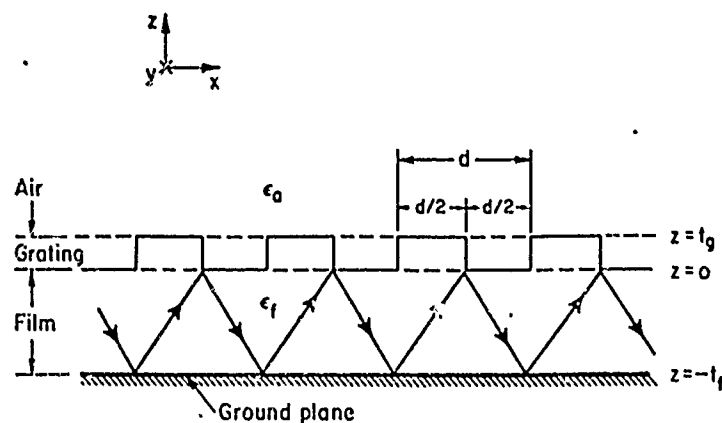
Fig. 1. Geometrical configuration of corrugated
dielectric antenna.
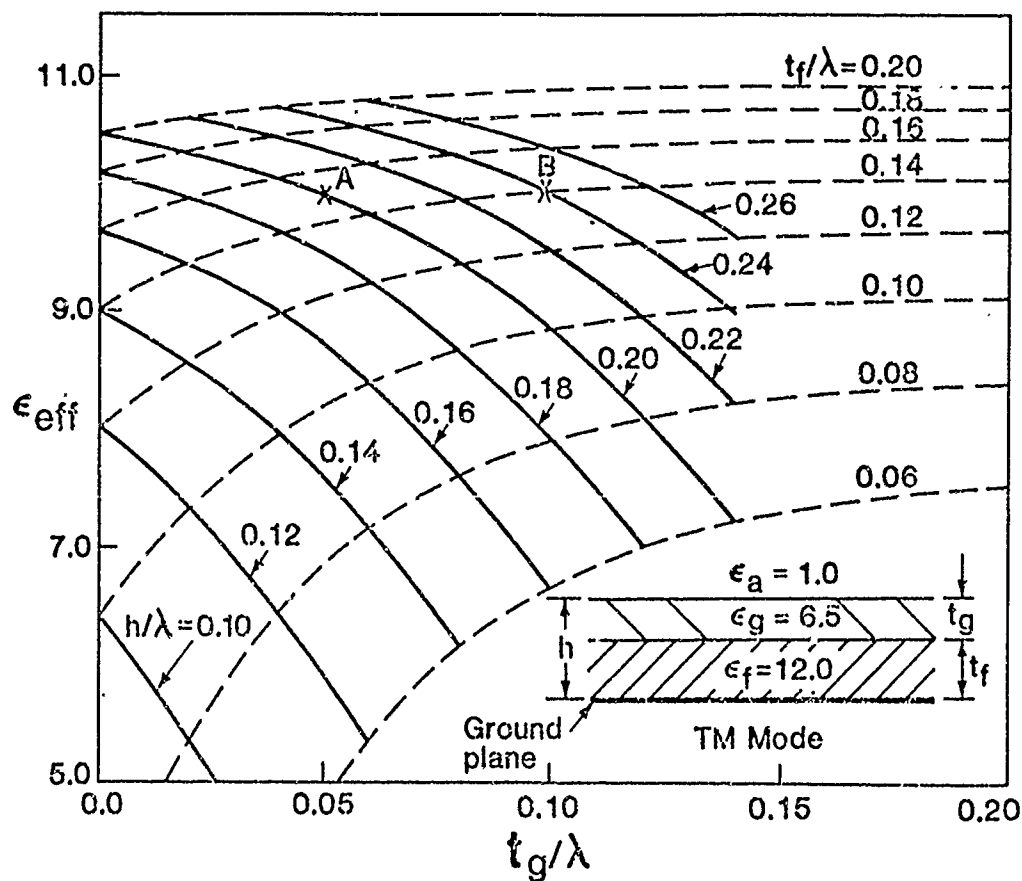
Fig. 2. Variations of effective dielectric constant vs corrugation
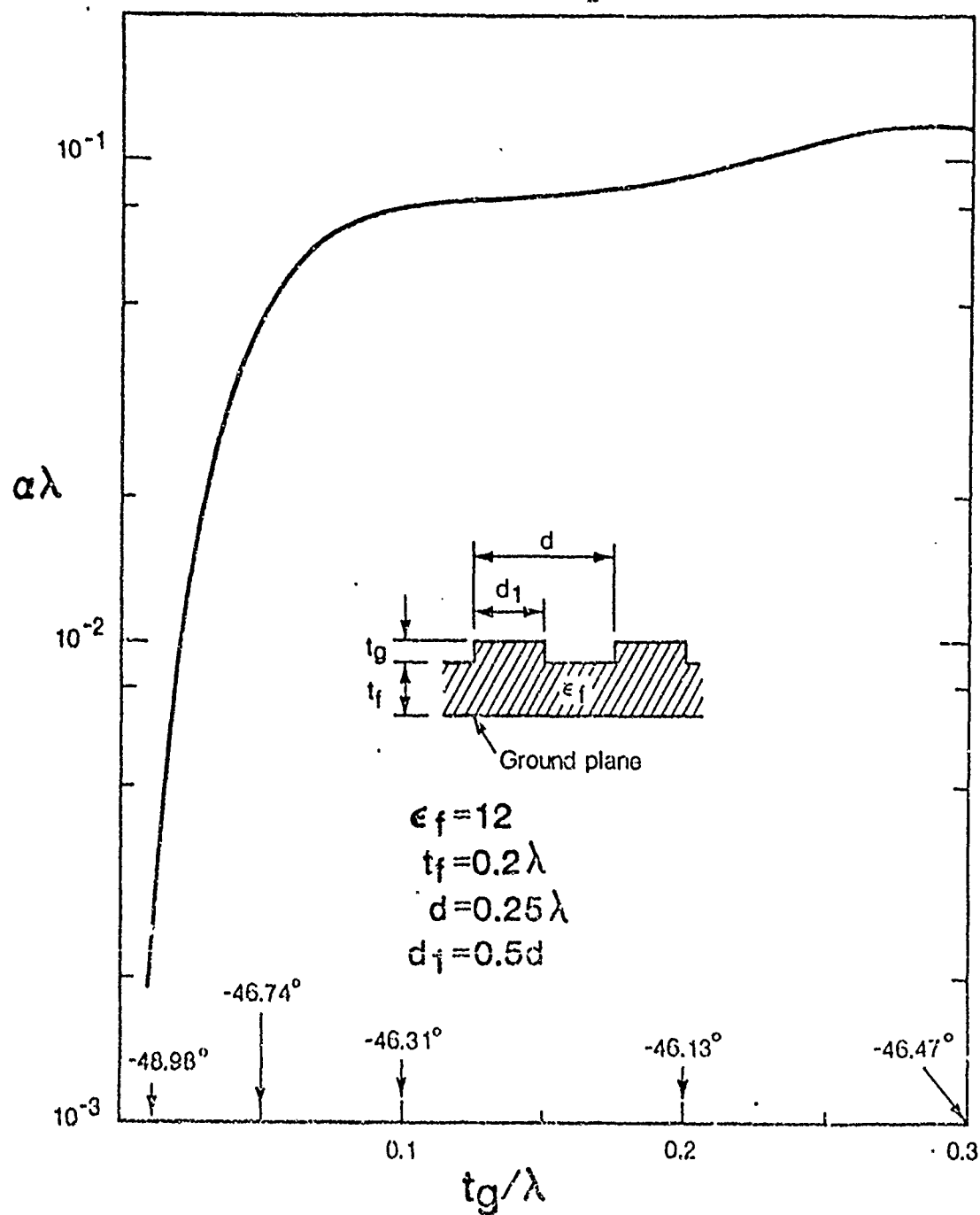depth t_g for uniform double-layer waveguide.

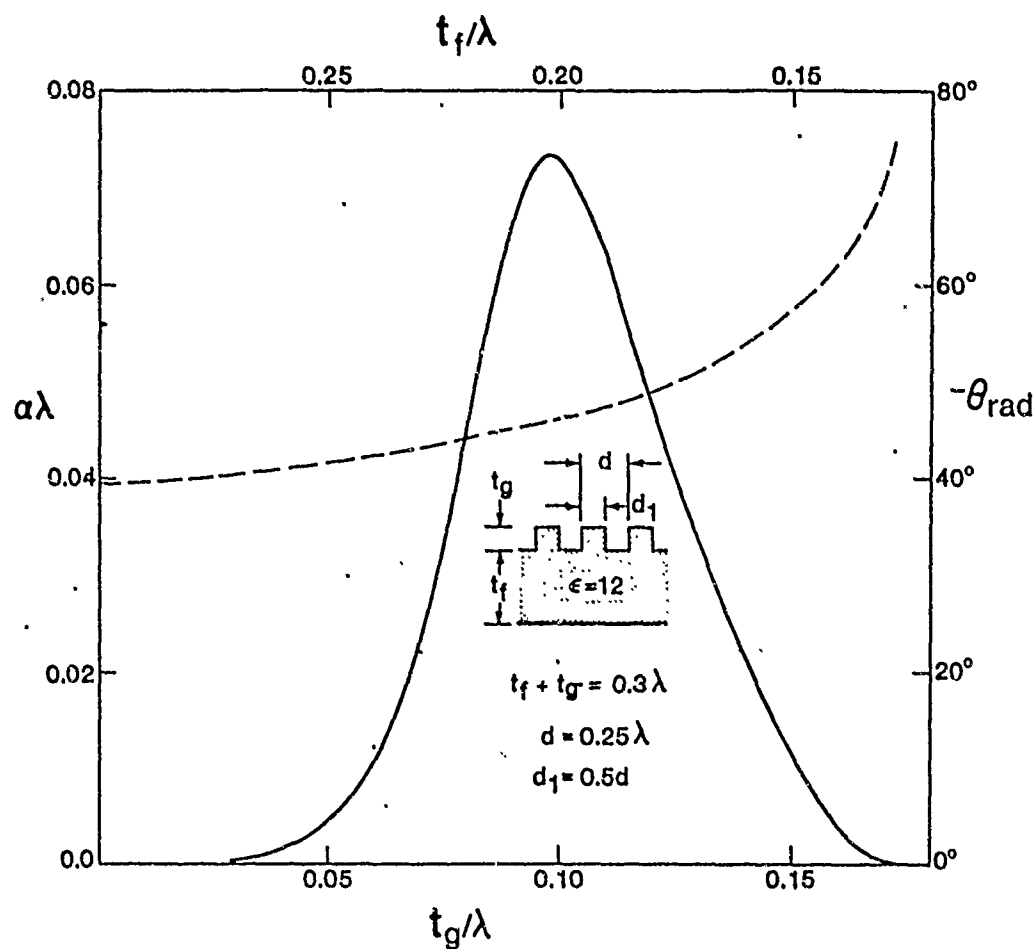Fig. 3. Variations of radiation constant vs. corrugation depth t_g for fixed thickness of the uniform region.

Fig. 4. Variations of radiation constant vs. corrugation depth for $t_f + t_g = 0.3\lambda$, $d = 0.25\lambda$ and $d_1 = 0.5d$.
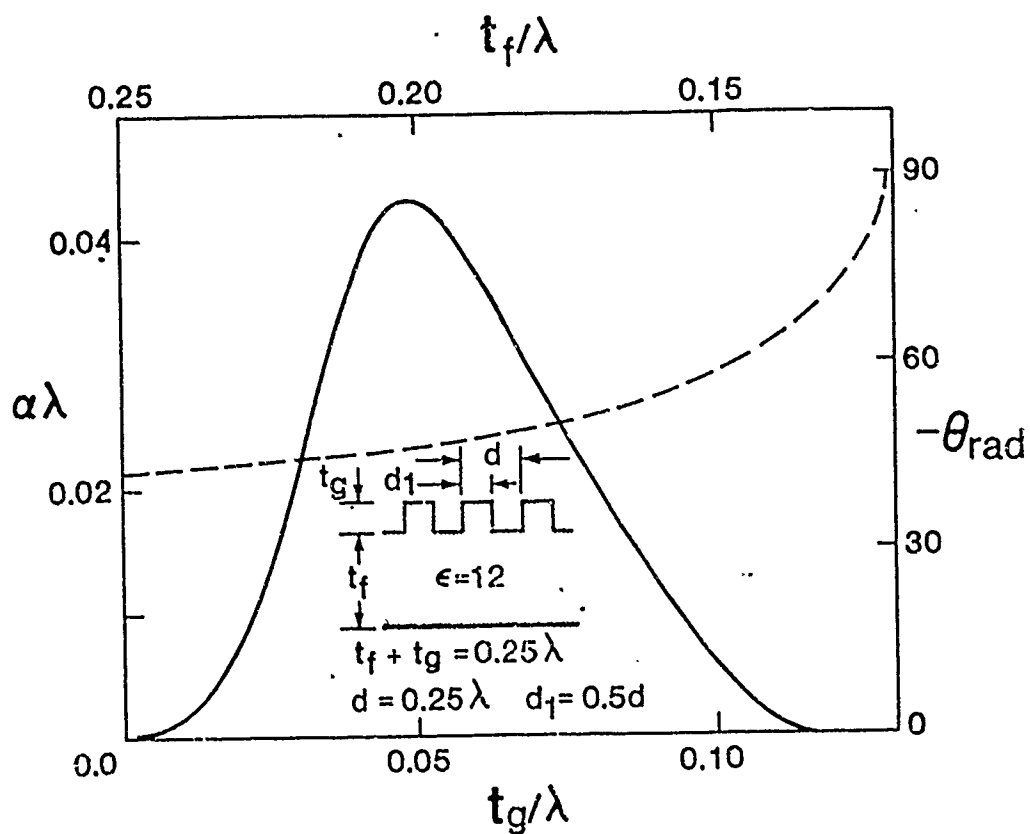
Fig. 5. Variations of radiation constant vs. corrugation depth
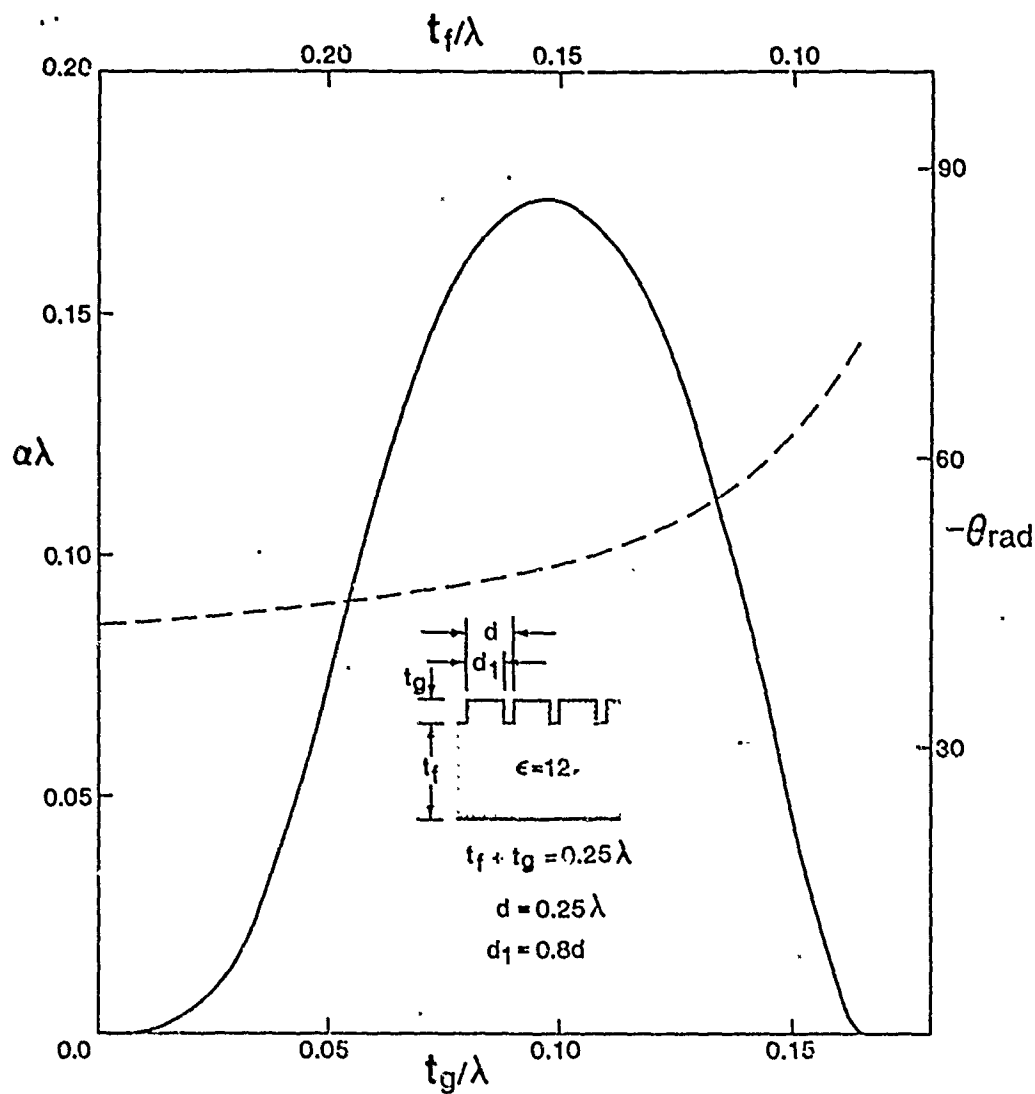for $t_f + t_g = 0.25 \lambda$, $d = 0.25 \lambda$ and $d_1 - 0.8d$.

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Fig. 6. Variations of radiation constant vs. corrugation depth for $t_f + t_g = 0.25\lambda$, $d = 0.25\lambda$ and $d_1 = 0.8d$.
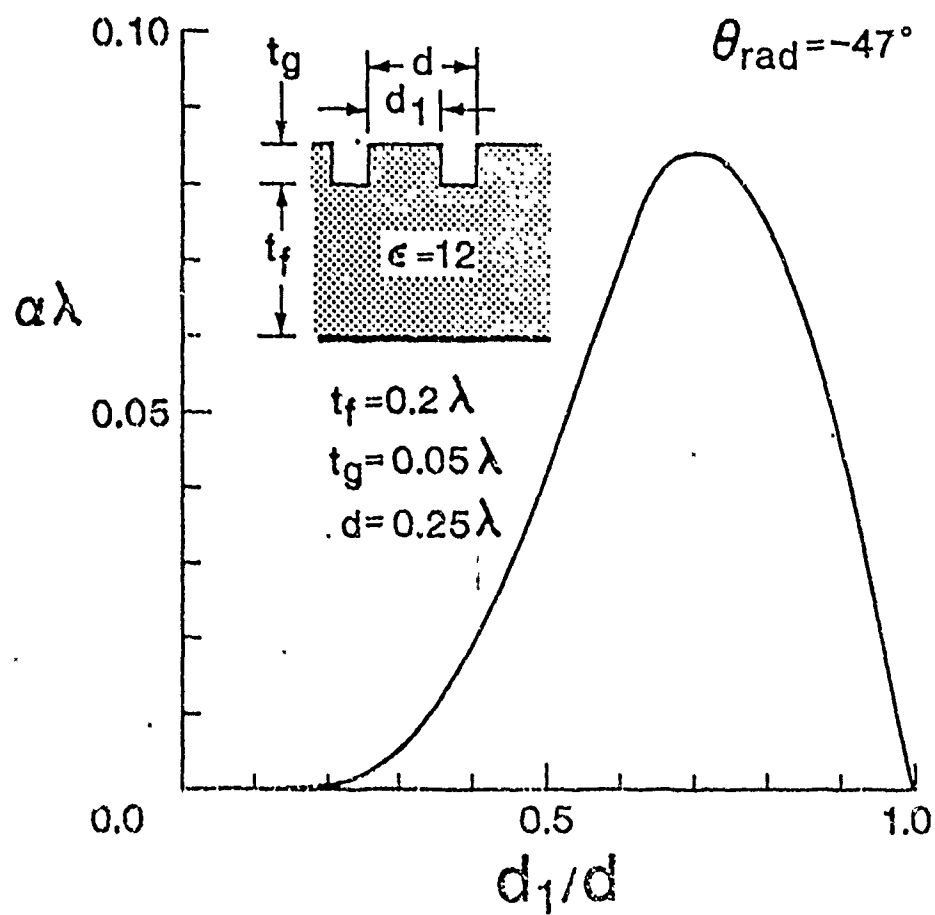
Fig. 7. Variations of radiation constant vs. aspect ratio d_1/d for $t_f + t_g = 0.25\lambda$, $t_g = 0.05\lambda$, and $d_1 = 0.5d$.

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